GRAN/IR/IN/90
2001/101/187

# CALIFORNIA INSTITUTE OF TECHNOLOGY

**Lindhurst Laboratory of Experimental Geophysics**
Seismological Laboratory 252-21, 1200 E. California Blvd.
Pasadena, CA 91125

June 25, 2001

*Thomas J. Ahrens*
*W. M. Keck Professor of Earth Sciences*
*and Professor of Geophysics*

"Impact and Collisional Processes in the Solar System"

NASA NAG5-3644

(CIT #: TJA.64514-1-NASA.645140)

Final Report

October 1, 1996 to March 31, 2000

Thomas J. Ahrens
Principal Investigator

cy: Dr. David Senske (NASA)
ONR, San Diego
NASA Center for Aerospace Information, Hanover MD
Spons. Res.
Patents Office
Project Accounting (letter only)

E-MAIL: tja@caltech.edu • TELEPHONE# (626) 395-6906 • FAX# (626) 564-0715, 568-0935
WEB ADDRESS: http://www.gps.caltech.edu/~ahrens

## ACCOMPLISHMENTS:

A series of impact experiments on anhydrite $CaSO_4$ in which vaporized sample accelerates an element in a velocity interferometer, generate velocity data that we have recently reanalyzed using an explicit entropy generating finite difference code. The shock pressure required from the onset, and complete vaporization of 30% porous (19 ± 2.8 and 98.7 ± 11.3 GPa) and 70% crystal density anhydrite is 52 ± 3 and 122 ± 13 GPa. (These initial data were later revised as explained below). Using observed acid leaching in non-marine K/T ejecta in N. America, and the sharp global increase in $^{87}Sr/^{86}Sr$ ratios recorded at 65 Ma in marine rocks, we demonstrated that global acidification is primarily due to the $SO_2$ released by anhydrite volatilization, and not $HNO_3$ formed from bolide-induced air pyrolysis. Shock temperatures for crystal $CaCO_3$ are measured from 3000 to 7000 K in the 90 to 160 GPa pressure range. These temperatures are much lower than calculated theoretically indicating that possibly bond breakdown at the shock front is occurring. This is the first mineral in which this effect has ever been seen. New data defining the ion species which are produced upon impact of volatilization of metals and minerals using a pulse UV laser to simulate intense shock heating from a projectile impact indicate that in shock experiments we can for the first time study the speciation of neutrals using a moderate resolution (0.2 dalton) time-of-flight mass spectrometer. Measurements of the gas species from a series of proposed impact experiments appear to be quite feasible. We will attempt these experiments in the next year. Measurements of the impact induced shock wave decay in $SiO_2$ and $GeO_2$ glass are underway to measure these pure oxide properties. Predictive calculations indicate that the pressure will decay as $r^{-2.7}$ in the phase transition regime, versus a much lower rate of $r^{-1.18}$, if a phase transition does not occur.

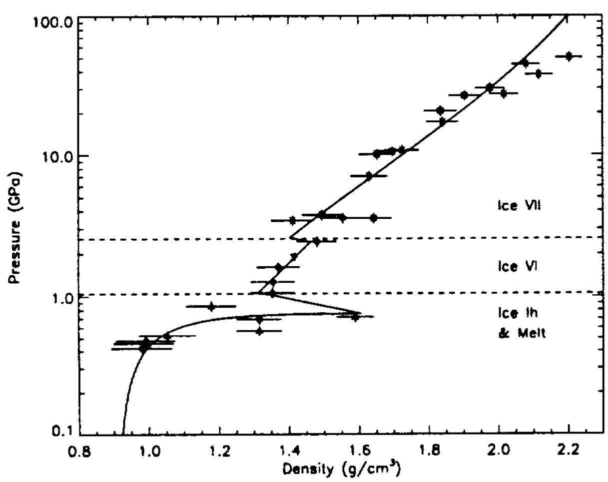
We have successfully developed the techniques necessary to conduct impact experiments on ice at very low temperatures. We employ the method of embedding gauges within a target to measure the shock wave and material properties. This means that our data are not model dependent; we directly measure the essential parameters needed for numerical simulations of impact cratering. Our preliminary experiments are published in Stewart and Ahrens [2000]. Since then we have developed a new method for temperature control of icy targets that ensures temperature equilibrium throughout a porous target. Graduate student, Sarah Stewart-Mukhopadhyay, is leading the work on ices and porous materials as the main thrust of her thesis research.

The work on ice and ice-silicate mixtures follows our previous work: "Low-velocity impact craters in ice and ice-saturated sand with implications for martian crater count ages" Croft et al. [1979], "Identification of ice VI on the Hugoniot of ice $I_h$" Gaffney and Ahrens [1980], "Fragmentation of ice by low velocity impact" Lange and Ahrens [1981], "The dynamic tensile strength of ice and ice-silicate mixtures" Lange and Ahrens [1983], and "Impact experiments in low-temperature ice" Lange and Ahrens [1987]. Our previous work has focused on icy materials with no porosity, and we propose to extend our research to include porous ice and porous ice-silicate mixtures. There is little shockwave data for porous ice [*Bakanova et al.*, 1976; *Furnish and Boslough*, 1996], and none of the data was acquired under conditions applicable to the outer solar system. The solid ice Hugoniot is only defined for initial temperatures above –20C [*Gaffney*, 1985].

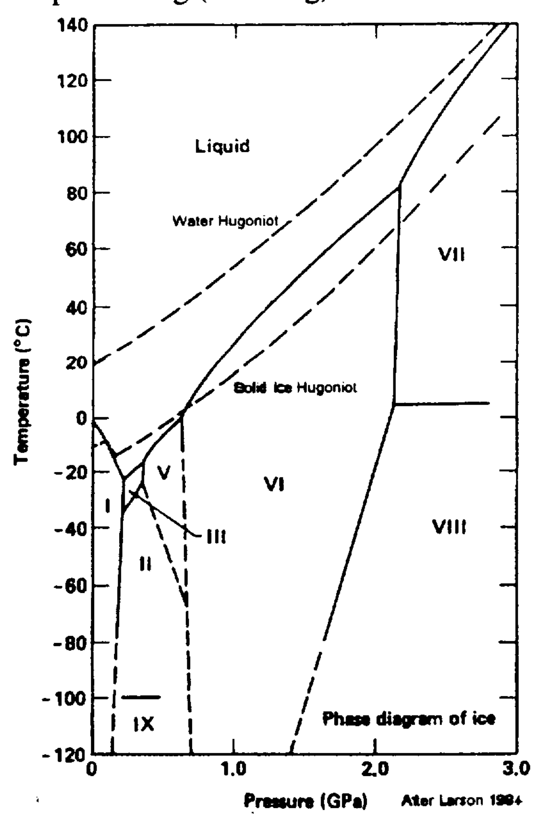
Our program uniquely measures the properties of ice at temperatures directly applicable to the solar system. Previous experiments were conducted at ambient temperatures soon after removing the target from a cold environment, usually just below freezing, or in a room just below freezing (e.g. Arakawa [1999]). Since ice has an extremely complicated phase diagram, see Figure 1, it is important to conduct experiments at lower temperatures to determine the true outcome of impacts in the outer solar system (e.g. Gaffney and Matson [1980]).

Our work has focused on the inherent material properties by measuring the shock wave directly; this complements the macroscopic observations and immediately provides the parameters necessary to extend this research to the gravity regime.

Our numerical simulations of impacts in porous ice under very low gravity conditions, such as found on comets, show that the final crater size and shape is very dependent on the dynamic strength of the material. There is some controversy over whether or not solid ice has a Hugoniot Elastic Limit (HEL), the maximum dynamic stress the material may bear before yielding. The data, based primarily on experiments near −10C, have alternatively been interpreted as a phase change (melting) instead of an HEL. This demonstrates the importance of conducting experiments at the appropriate temperature to understand the ice phases involved. Until our research, there has never been a measurement of the HEL in porous ice and it was assumed that porous ice had no inherent dynamic strength. We have discovered a small HEL in porous ice. We are conducting further experiments to verify this detection and understand its porosity and temperature dependence as well as the effects of thermal processing (sintering).

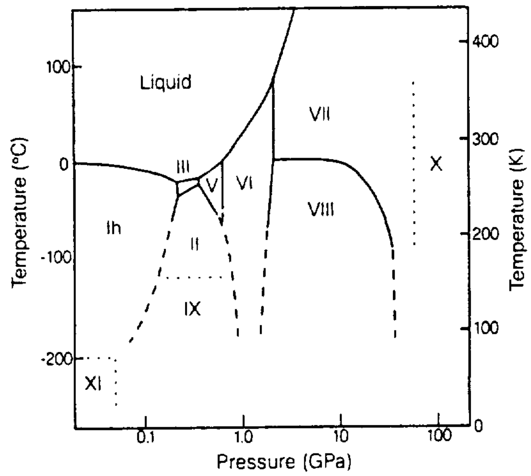



(a) Solid Ice Hugoniot centered at −10C, 1 bar. Data from Gaffney [1985], 3σ error bars.




(b) (after Larson [1984])

FIGURE 1. Importance of initial temperature on shock Hugoniot of $H_2O$. (a) The different segments of




(c) $H_2O$ Phase Diagram [*Lobban et al.*, 1998]

the ice Hugoniot centered at −10C correspond to the shocked phase as illustrated in (b). (b) An estimate of the path of the ice Hugoniot shown in (a). (c) $H_2O$ phase diagram down to absolute zero. The importance of the initial temperature is evident from the many different phases of ice that can be reached by moderate shock pressures.

We have conducted more recovery experiments to measure sound velocity deficits in shock-damaged materials, and we are working on relating the deficits to the impact conditions: impact velocity and projectile mass.

Ultrasonic velocities are a good indicator of impact damage because the wave speed is a strong function of the crack or pore density in the material (e.g. O'Connell and Budiansky [1977]).

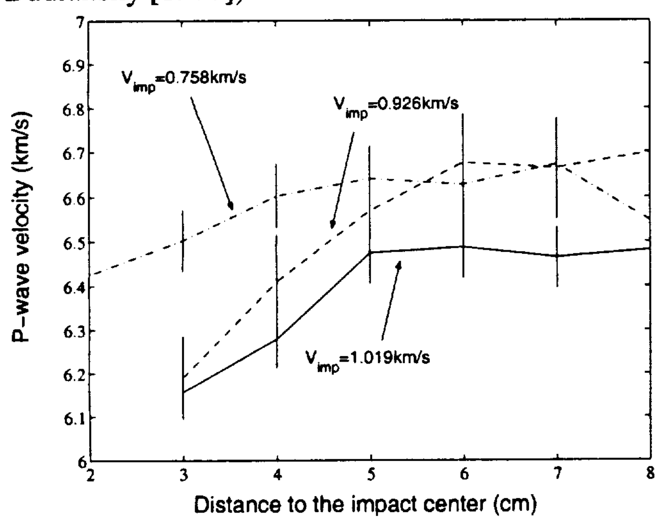



Figure 2. P-wave velocities in San Marcos gabbro. The sound speed is measured in targets impacted with a spherical Al projectile at the noted velocity. The data shown are from directly beneath the center of the crater. The sound speed deficit near the crater indicates impact damage. The higher the impact velocity, the lower the wave speed, and the larger the impact damage. The regions further from the crater remain undamaged and retain the pre-impact wave speeds. The difference in undamaged sound velocities between the samples is attributed to heterogeneities in San Marcos gabbro. 3σ error bars.

There is currently very little work in this area in the geophysics community whereas headway has been made in the ceramics community (e.g. Camacho and Ortiz [1996]). Our previous work includes: "Mechanical properties of shock-damaged rocks" He and Ahrens [1994] and "Stress wave attenuation in shock damaged rock" Liu and Ahrens [1997]. Our examination of the literature on terrestrial impact craters (e.g. Pilkington and Grieve [1992]) shows that there seems to be a log-log relationship between the crater diameter and the depth of the impact-damaged zone [*Ahrens et al.*, 2001]. We are quantifying this relationship based on the impact physics and the new insight gained from the research on impact damage in ceramics. Our program on impact damage in geologic materials will allow the planetary science community to quantify the effects of cratering in another dimension: below the surface. We also expect to conduct multiple impact experiments to understand cratering in previously damaged materials.

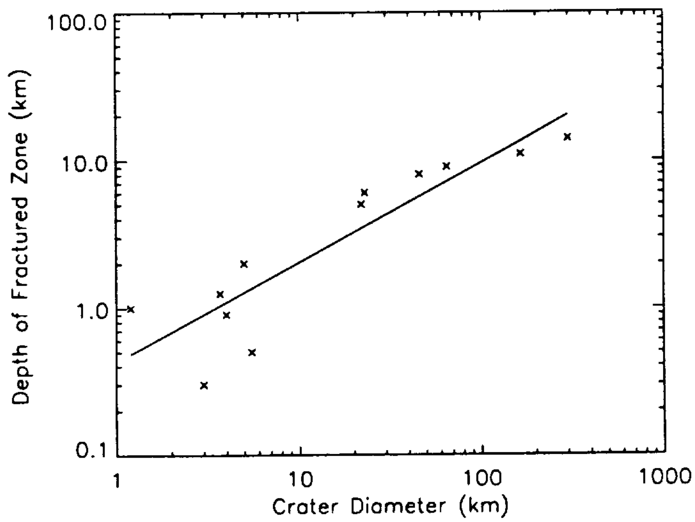



Figure 3. Damaged zones beneath terrestrial craters inferred from seismic refraction measurements. Using published data, we have estimated the relationship between the crater diameter and the depth of the damaged zone for a dozen terrestrial craters. This empirical relationship has not yet been explained quantitatively. The least squares fit is log H (km) = -0.367 + 0.673 log D (km) where D is the crater diameter and H is the depth of the damaged zone.

We have revisited the question of how much vapor was produced from the K/T impact [*Gupta et al.*, 2001]. New analysis of data on shock vaporization of anhydrite [*Yang and Ahrens*, 1998] has produced revised values for the shock pressures required for incipient and complete vaporization. Together with a revised size for the transient diameter of the Chicxulub crater [*O'Keefe and Ahrens*, 1999], the amount of sulfuric vapor that could have produced sulfuric acid aerosols has been decreased to 11-39 gigatons, compared to 200 gigatons estimated by Pope et al. [1997]. Assuming a maximum production of sulfuric acid aerosols, the global temperature decreased 12-19K for about a decade, compared to the 5-31 K drop for 12 years reported by Pope et al. [1997]. Since the Earth's surface temperature during the K/T epoch was 18-20K warmer than present values (e.g. Savin and Yeh [1981]), this cooling event could not produce global freezing conditions at the Earth's surface.

Even with this new result, the global effects of the K/T impact cannot be accurately assessed without an understanding of the speciation in the vapor plume. If most of the sulfur ends up in $SO_2$, the global impact may still be considerable and long-lived. We have been developing a method to detect impact vapor species using a time-of-flight mass spectrometer (TOFMS).

Another application of impact volatilization is the accretion of the Earth and the role of serpentine, which is illustrated by the following reactions:

$$\underset{\text{(serpentine)}}{Mg_3Si_2O_5(OH)_4} \rightarrow \underset{\text{(forsterite)}}{Mg_2SiO_4} + \underset{\text{(enstatite)}}{MgSiO_3} + \underset{\text{(water)}}{2H_2O} \quad (1)$$

$$\underset{\text{(enstatite)}}{MgSiO_3} + \underset{\text{(iron)}}{Fe} + \underset{\text{(water)}}{H_2O} \rightarrow \underset{\text{(fayalite)}}{\frac{1}{2}\,Fe_2SiO_4} + \underset{\text{(forsterite)}}{\frac{1}{2}\,Mg_2SiO_4} + \underset{\text{(hydrogen)}}{H_2} \quad (2)$$

Under this grant, we conducted a detailed study of reaction (1), which included determining the Hugoniot of serpentine (e.g. Tyburczy [2001]; Tyburczy et al. [1991];

Tyburczy [1990], Ahrens [1990]). We also note that serpentine is one of the most abundant hydrous minerals in primitive meteorites [*Lange et al.*, 1985; *Ringwood*, 1979]. It has been inferred that serpentine was abundant in planetesimals and was the carrier of most of the water to the terrestrial planets. Abe and Matsui [1985] directly utilized the Caltech impact devolatilization data on serpentine to define their model of a super greenhouse overlying a magma ocean during accretion of the Earth, a condition that prevailed for a large fraction of the accumulation of the planet. After about 0.26 of the final mass of the Earth had accreted, further impacts devolatilized creating a thick hydrosphere.

## References and Published Papers (*).


Abe, Y., and T. Matsui, The formation of an impact-generated $H_2O$ atmosphere and its implications for the early thermal history of the Earth, *Proc. Lunar Planet. Sci. Conf. 15th, Part 2, J. Geophys. Res.*, *90*, C545-C559, 1985.

Ahrens, T.J., Earth Accretion, in *Origin of the Earth*, edited by J. Jones, and H. Newsom, pp. 211-227, Oxford U. Press, Oxford, 1990.

*Ahrens, T.J., K. Xia, D. Coker, and J.D. O'Keefe, Planetary impact and shock-induced damage in target rocks, in *2001 Shock Compression of Condensed Matter, June 24-29, 2001 (abstract)*, American Physical Society, Atlanta, Georgia, 2001.

Arakawa, M., Collisional disruption of ice by high-velocity impact, *Icarus*, *142* ((1)), 34-45, 1999.

Bakanova, A.A., V.N. Zubarev, Y.N. Sutulov, and R.F. Trunin, Thermodynamic properties of water at high pressures and temperatures, *Sov. Phys. JETP (originally published Zh. Eksp. Teor. Fiz. 68, 1099-1107, 1975)*, *41*, 544-548, 1976.

Camacho, G.T., and M. Ortiz, Computational modeling of impact damage in brittle materials, *Intl. J. Solid Structures*, *33* (20-22), 2899-2938, 1996.

Croft, S.K., S.W. Kieffer, and T.J. Ahrens, Low-velocity impact craters in ice and ice-saturated sand with implications for Martian crater count ages, *J. Geophys. Res.*, *84*, 8023-8032, 1979.

Furnish, M.D., and M.B. Boslough, Measuring Hugoniot, reshock and release properties of natural snow and simulants, Sandia National Laboratories, 1996.

Gaffney, E.S., Hugoniot of water ice, in *Ices in the Solar System*, edited by J. Klinger, D. Benest, A. Dollfus, and R. Smoluchowski, pp. 119-148, NATO ASI Series, January 16-19, 1984, Nice, France, 1985.

Gaffney, E.S., and T.J. Ahrens, Identification of ice VI on the Hugoniot of ice $I_h$, *Geophys. Res. Lett.*, *7*, 407-409, 1980.

Gaffney, E.S., and D.L. Matson, Water ice polymorphs and their significance on planetary surfaces, *Icarus*, *44*, 511-519, 1980.

*Gupta, S.C., T.J. Ahrens, and W. Yang, Shock-induced vaporization of anhydrite and global cooling from the K/T impact, *Earth Planet. Sci. Lett. (in press)*, 2001.

He, H., and T.J. Ahrens, Mechanical properties of shock-damaged rocks, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, *31*, 525-533, 1994.

Lange, M., and T.J. Ahrens, Fragmentation of ice by low velocity impact, in *Proc. Lunar and Planet. Sci. Conf.*, pp. 1667-1687, Pergamon Press, Houston, TX, 1981.

Lange, M.A., and T.J. Ahrens, The dynamic tensile strength of ice and ice-silicate mixtures, *J. Geophys. Res.*, *88*, 1197-1208, 1983.

Lange, M.A., and T.J. Ahrens, Impact experiments in low temperature ice, *Icarus*, *69*, 506-518, 1987.

Lange, M.A., P. Lambert, and T.J. Ahrens, Shock effects on hydrous minerals and implications for carbonaceous meteorites, *Geochim. Cosmochim. Acta*, *49*, 1715-1726, 1985.

Larson, D.B., Shock-wave studies of ice under uniaxial strain condtions, *J. Glaciol.*, *30* ((105)), 235-240, 1984.

*Liu, C., and T.J. Ahrens, Stress wave attenuation in shock-damaged rock, *J. Geophys. Res.*, *102* (B3), 5243-5250, 1997.

Lobban, C., J.L. Finney, and W.F. Kuhs, The structure of a new phase of ice, *Nature*, *391* ((6664)), 268-270, 1998.

O'Connell, R.J., and B. Budiansky, Seismic velocities in dry and saturated cracked solids, *J. Geophys. Res.*, *79*, 5412-5426, 1977.

*O'Keefe, J.D., and T.J. Ahrens, Complex craters: Relationship of stratigraphy and rings to the impact conditions, *J. Geophys. Res.*, *104* (E11), 27,091-27,104, 1999.

Pilkington, M., and R.A.F. Grieve, The geophysical signature of terrestrial impact craters, *Rev. Geophys.*, *30* ((2)), 161-181, 1992.

Pope, K.O., K.H. Baines, A.C. Ocampo, and B.A. Ivanov, Energy, volatile production, and climatic effects of the Chicxulub Cretaceous/Tertiary impact, *J. Geophys. Res.*, *102 (E9)*, 21645-21664, 1997.

Ringwood, A.E., *Origin of the Earth and Moon*, 295 pp., Springer-Verlag, Berlin, New York, 1979.

Savin, S.M., and H.W. Yeh, Chapt. 33. Stable isotopes in ocean sediments, in *The Sea: The Ocean Lithosphere*, edited by C. Emiliani, pp. 1521-1554, Wiley-Interscience, New York, 1981.

*Stewart, S.T., and T.J. Ahrens, Shock wave propagation in porous ice, in *Shock Compression of Condensed Matter - 1999*, edited by M.D. Furnish, L.C. Chhabildas, and R.S. Hixon, pp. 1243-1246, AIP, Woodbury NY, 2000.

*Tyburczy, J.A., T.J. Ahrens, X. Xu, and S. Epstein, Shock-induced devolatilization and isotopic fractionation of H and C from Murchison Meteorite: Implications for planetary accretion, *Earth Planet. Sci. Lett.* (accepted for publication), 2001.

Tyburczy, J.A., T.S. Duffy, T.J. Ahrens, and M.A. Lange, Shock wave equation of state of serpentine to 150 GPa: Implications of the occurrence of water in the Earth's lower mantle, *J. Geophys. Res.*, *96*, 18011-18027, 1991.

Tyburczy, J.A., R.V. Krishnamurthy, S. Epstein, and T.J. Ahrens, Impact-induced devolatilization and hydrogen isotopic fractionation of serpentine: Implications for planetary accretion, *Earth Planet. Sci. Lett.*, *98*, 245-261, 1990.

*Yang, W., and T.J. Ahrens, Shock vaporization of anhydrite and global effects of the K/T bolide, *Earth Planet. Sci. Lett.*, *156*, 125-140, 1998.